To the Moon!
Space Launch System Modal Testing with Video and Motion Magnification

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The Mission

A B C

CUBESATS DEPLOY
ICPS deploys 10
CubeSats total

MISSION DURATIONS:
Total: 25 days, 10 hrs
Outbound Transit: 9 days 13 hrs
DRO Stay: 6 days 0 hrs
Return Transit: 9 days 19 hrs

ARTEMIS I

The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket

1. **LAUNCH (11/16/22)**
SLS and Orion lift off from pad 39B at Kennedy Space Center.

2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

3. **CORE STAGE MAIN ENGINE CUT OFF**
With separation.

4. **PERIGEE RAISE MANEUVER**

5. **EARTH ORBIT**
Systems check with solar panel adjustments.

6. **TRANS LUNAR INJECTION (TLI) BURN**
Maneuver lasts for approximately 20 minutes.

7. **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL**
ICPS commits Orion to moon at TLI.

8. **OUTBOUND TRAJECTORY CORRECTION BURNS**
As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).

9. **OUTBOUND POWERED FLYBY**
105.5 miles from the Moon; targets DRO insertion.

10. **LUNAR ORBIT INSERTION**
Enter Distant Retrograde Orbit.

11. **DISTANT RETROGRADE ORBIT**
Perform a half revolution (6 day duration) in the orbit 43,730 miles from the surface of the Moon.

12. **DRO DEPARTURE**
Leave DRO and start return to Earth.

13. **RETURN POWERED FLYBY**
RPF burn prep and return coast to Earth initiated. Closest approach in middle of burn, 81 miles.

14. **RETURN TRANSIT**
Return Trajectory Correction burns as necessary to aim for Earth's atmosphere.

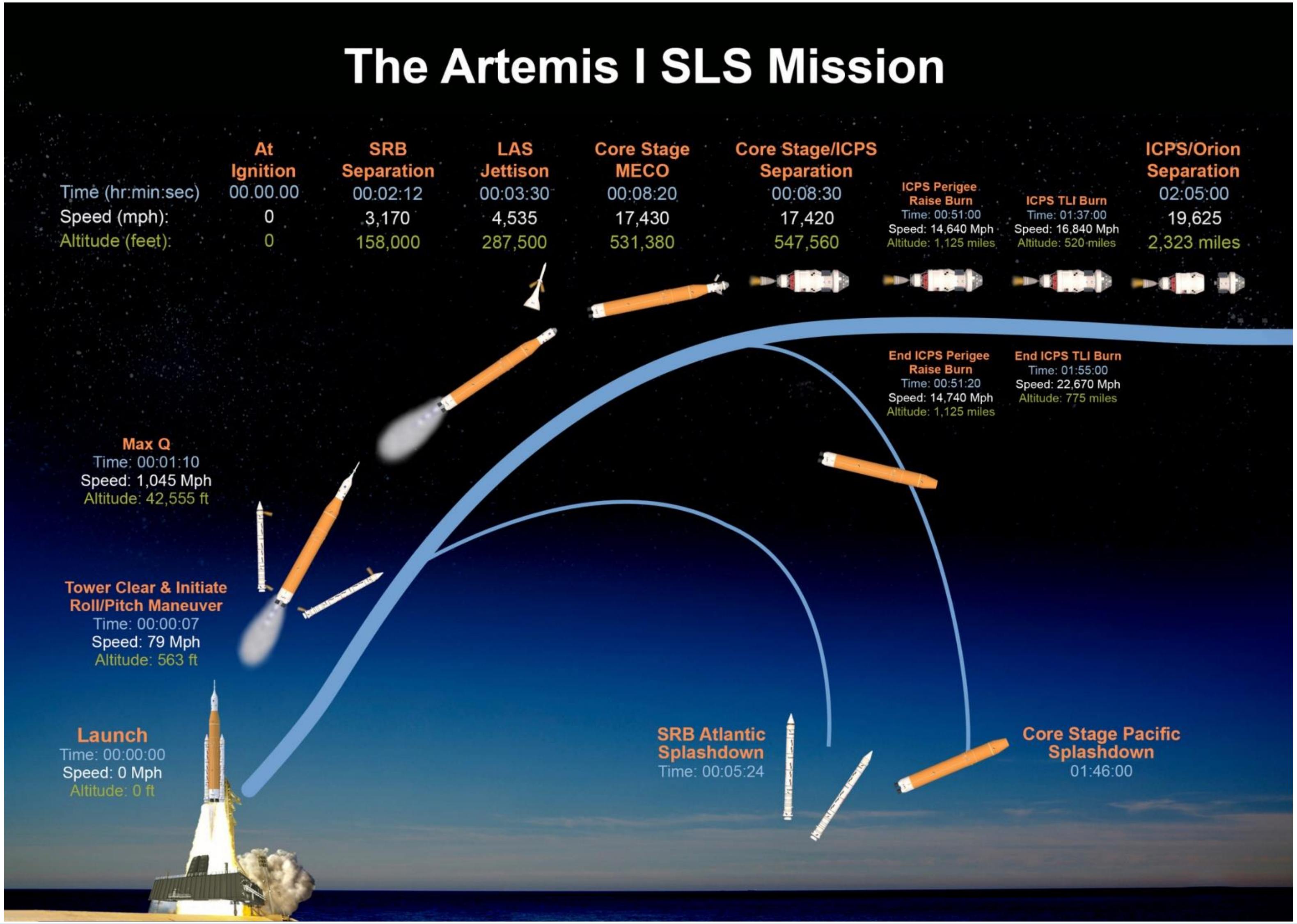
15. **CREW MODULE SEPARATION FROM SERVICE MODULE**

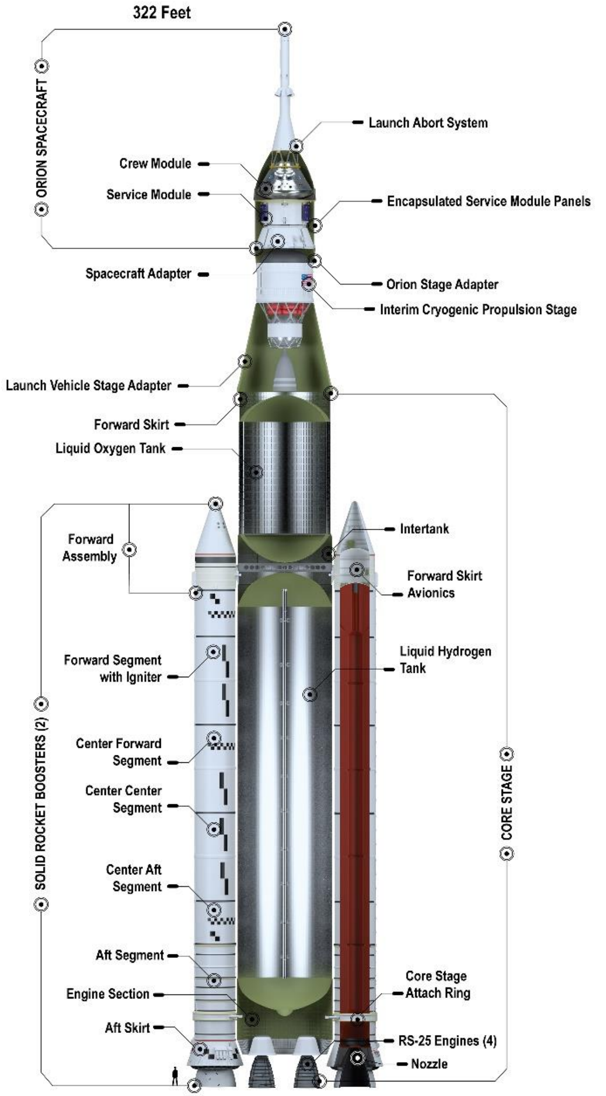
16. **ENTRY INTERFACE**
Enter Earth's atmosphere.

17. **SPLASHDOWN (12/11/22)**
Pacific Ocean landing within view of the U.S. Navy recovery ship.

https://www.nasa.gov/specials/artemis-i-press-kit/

The Rocket: Space Launch System



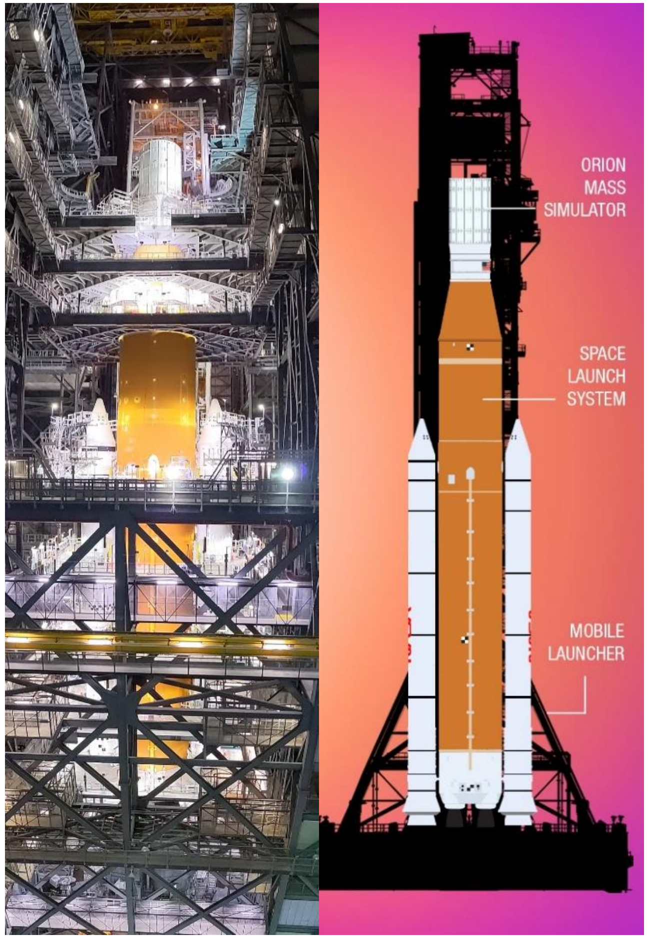


https://www.nasa.gov/specials/artemis-i-press-kit/

Integrated Modal Test (IMT) and Dynamic Rollout/Rollback Test (DRRT)

IMT: Integrated Modal Test

- **A modal test of the fully integrated rocket stack except for a mass simulator replacing the Orion capsule**
- **Different boundary conditions, shakers, and excitations (random vibe, and sine sweep) are used to measure the mode shapes of the vehicle**



DRRT: Dynamic Rollout/Rollback Test

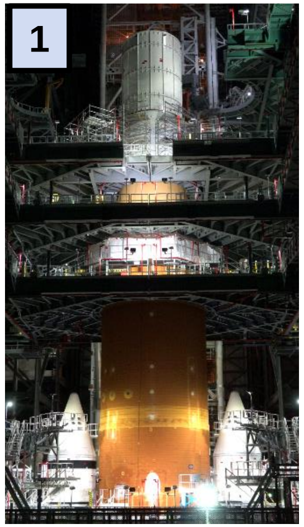
- **The Crawler-Transporter (CT) carries the Mobile Launcher (ML) and fully stacked SLS rocket on a ~4 mile journey from the VAB to Launch Complex 39B**
- **During this journey the CT travels up to a top speed of 0.8 mph, which vibrates the rocket**
- **The rocket has accelerometers to monitor for vibrations that may exceed designated safe levels as well as measure operational vibration modes**

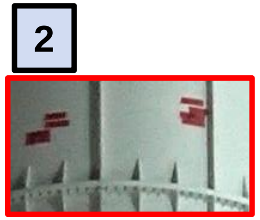
Video cameras offer quick setup and instrumentation of a wide field of view vs. point sensors. How well do they work in real world testing of large structures?

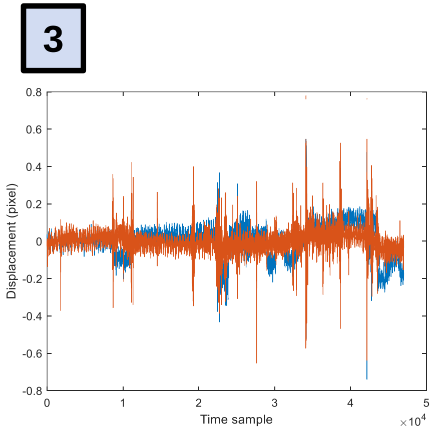
From: https://www.nasa.gov/exploration/systems/sls/modal-testing-infographic.html

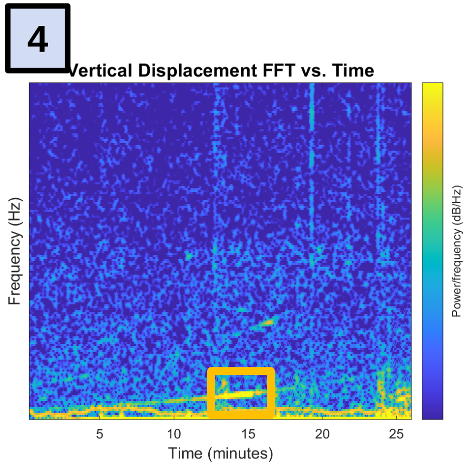
Video Workflow

1. **Record video of a structure/vehicle under test**
2. **Manually choose an ROI to crop the video**
3. **Extract a displacement time series from the cropped ROI to process for potential operational modes of interest**
4. **Use an FFT and/or Spectrogram of the displacement to figure out the frequency range, amplification factor, and segment of the video to magnify**
5. **Motion magnify the video segment and (hopefully) see an operational mode shape**

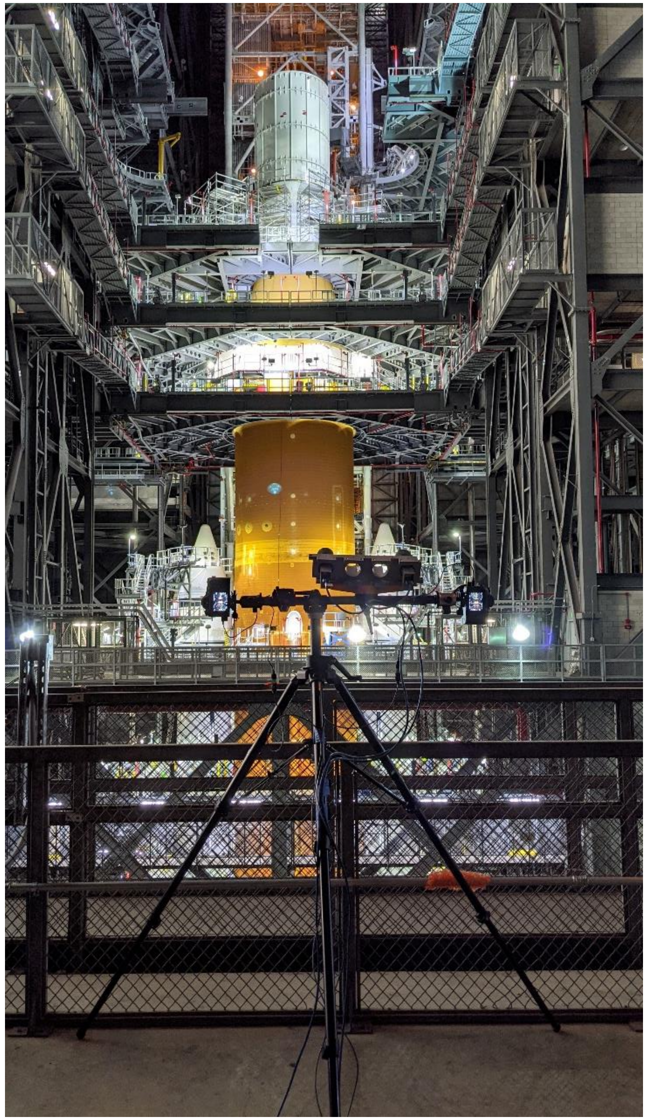




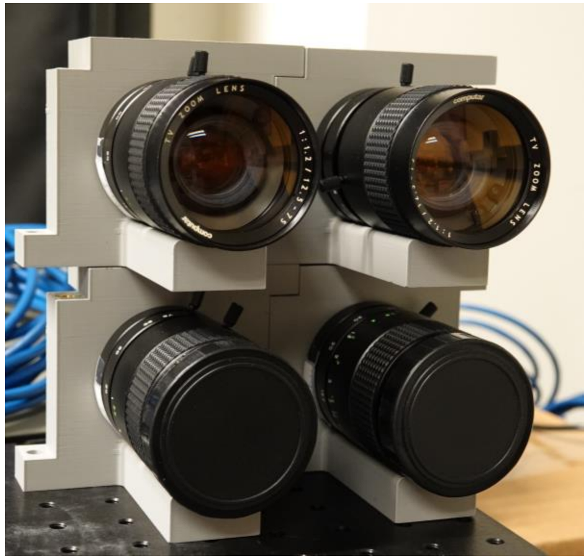




IMT Camera Measurements: Setup

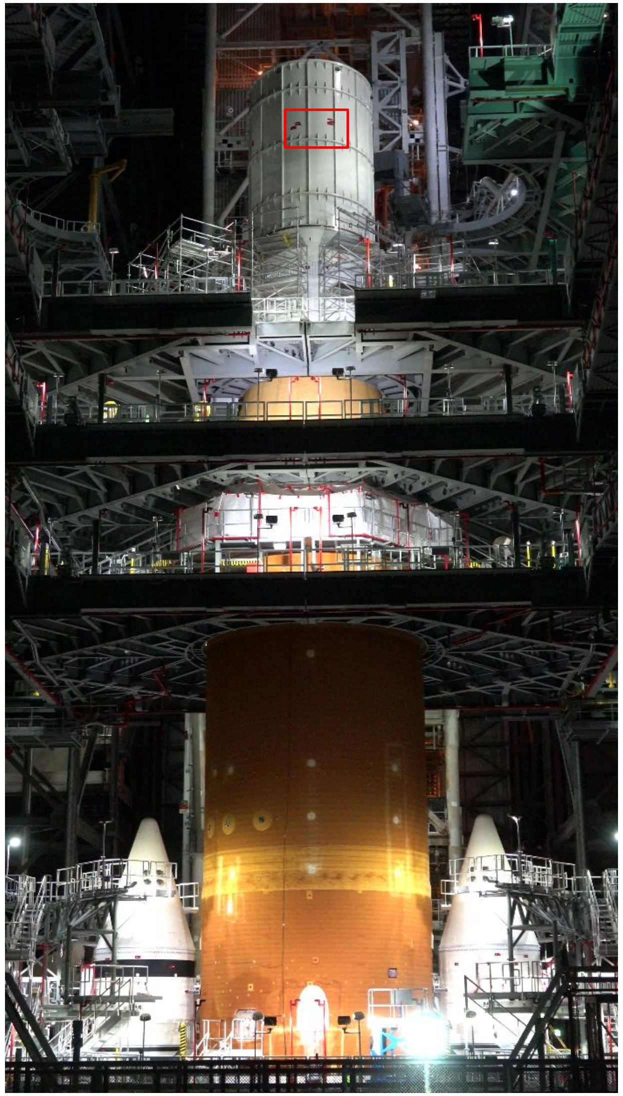


- **Cameras were placed on the 16th floor across the transfer aisle in High Bay 4**
  - **Offered a good view of the top of the SRBs, core stage, and MSO**
- **Later, measurements were made from different locations to capture the behavior of the fore and aft SRB attachment points**
- **Video was recorded at 30fps, above the Nyquist frequency for most modes of interest**
- **Cameras and specifications:**
  - **Sony Consumer Camera**
    - **3840x2160 at 30fps, Rolling Shutter**
  - **Point Grey/FLIR Machine Vision Camera x2**
    - **800x800 at 30fps, Global Shutter**

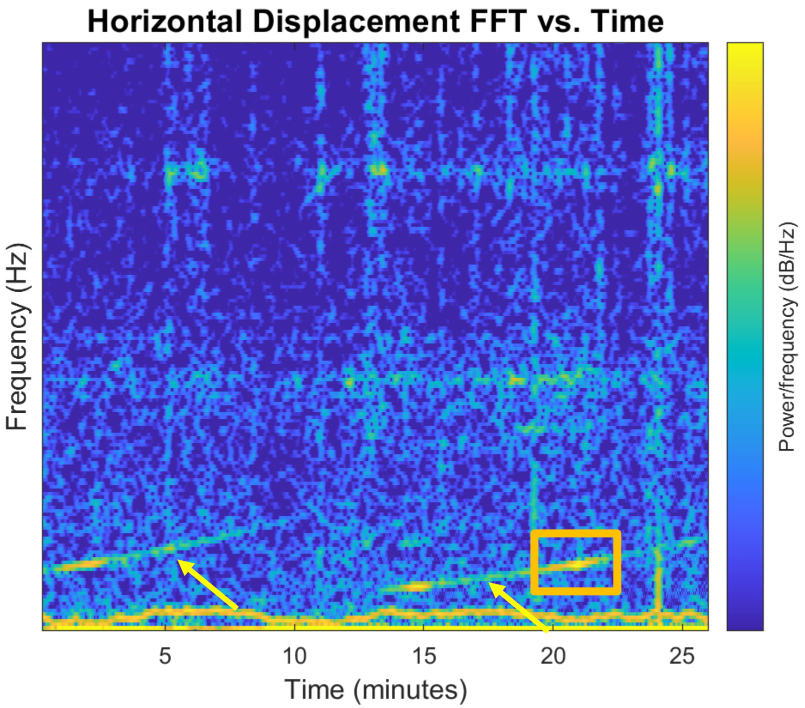


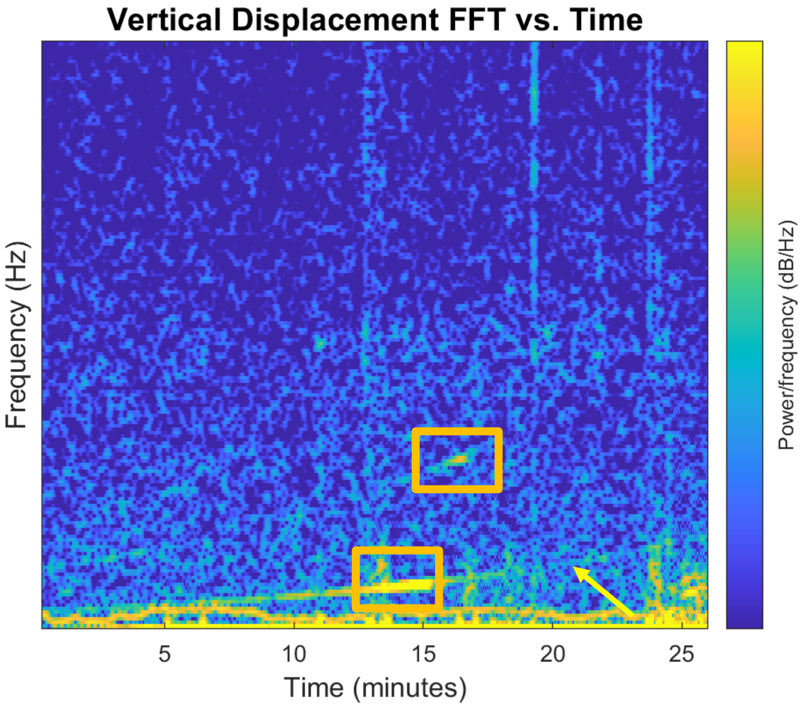
SRB: Solid Rocket Booster
MSO: Mass Simulator for Orion

Sine Sweep Excitation: 10-Point Test



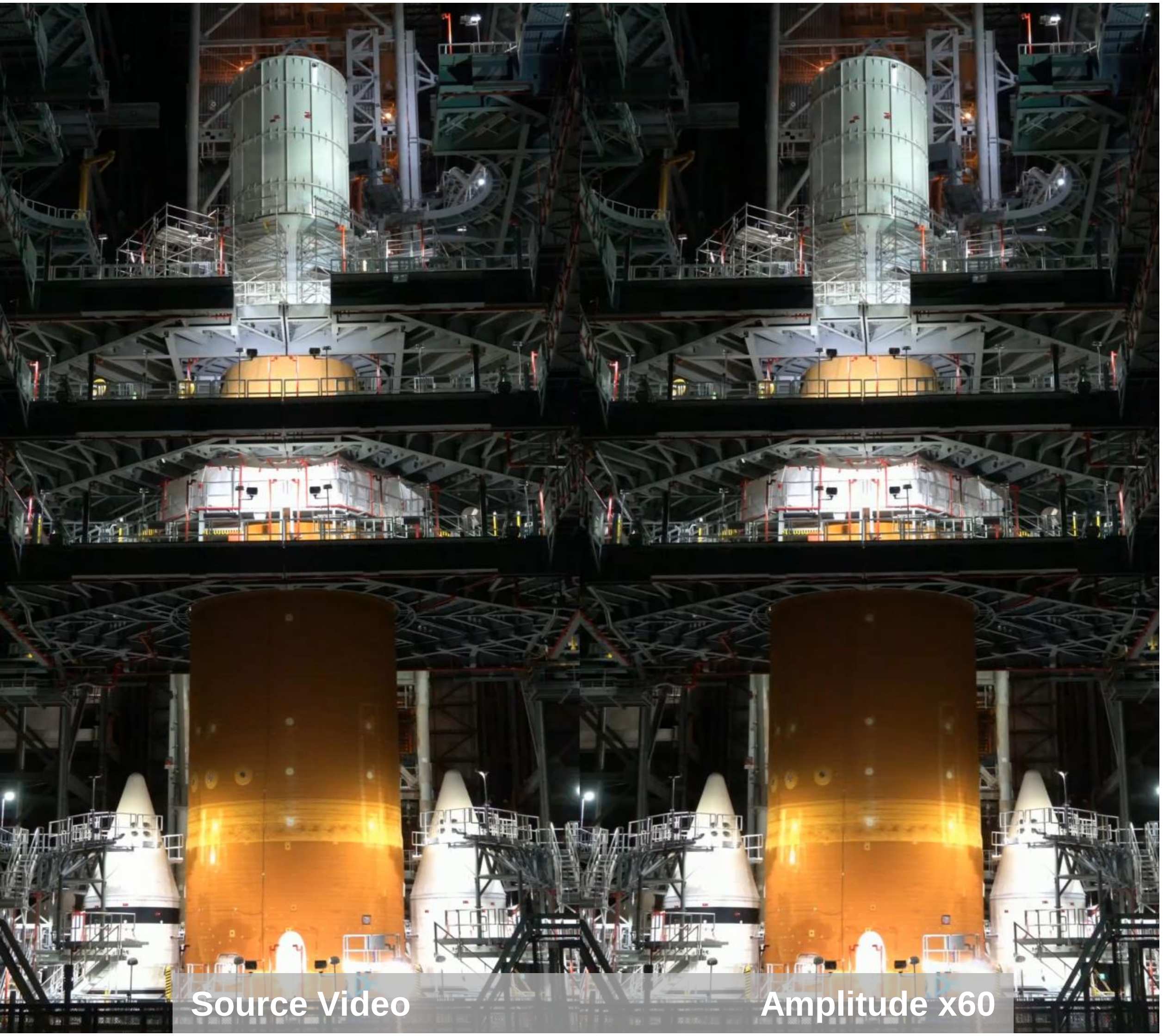
- Displacements were extracted from an region of interest on the MSO and plotted as a spectrogram
- The sine sweep can be seen in the measured spectrogram (arrows)
- Excited modes can be see as bright spots in the excitation signal which represent more motion (boxes)



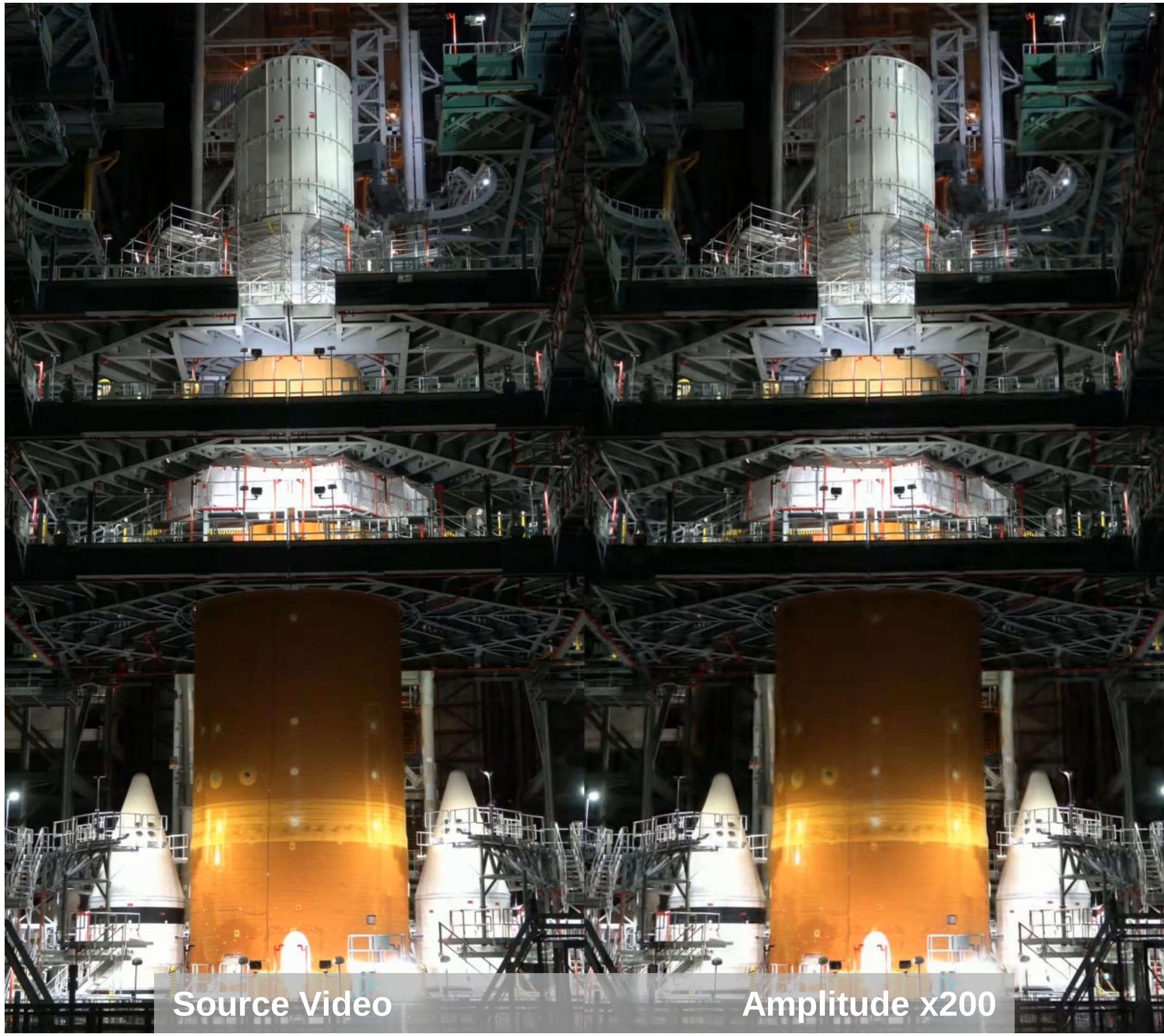


MSO: Mass Simulator for Orion

Rocking Modes – 10-Point Test

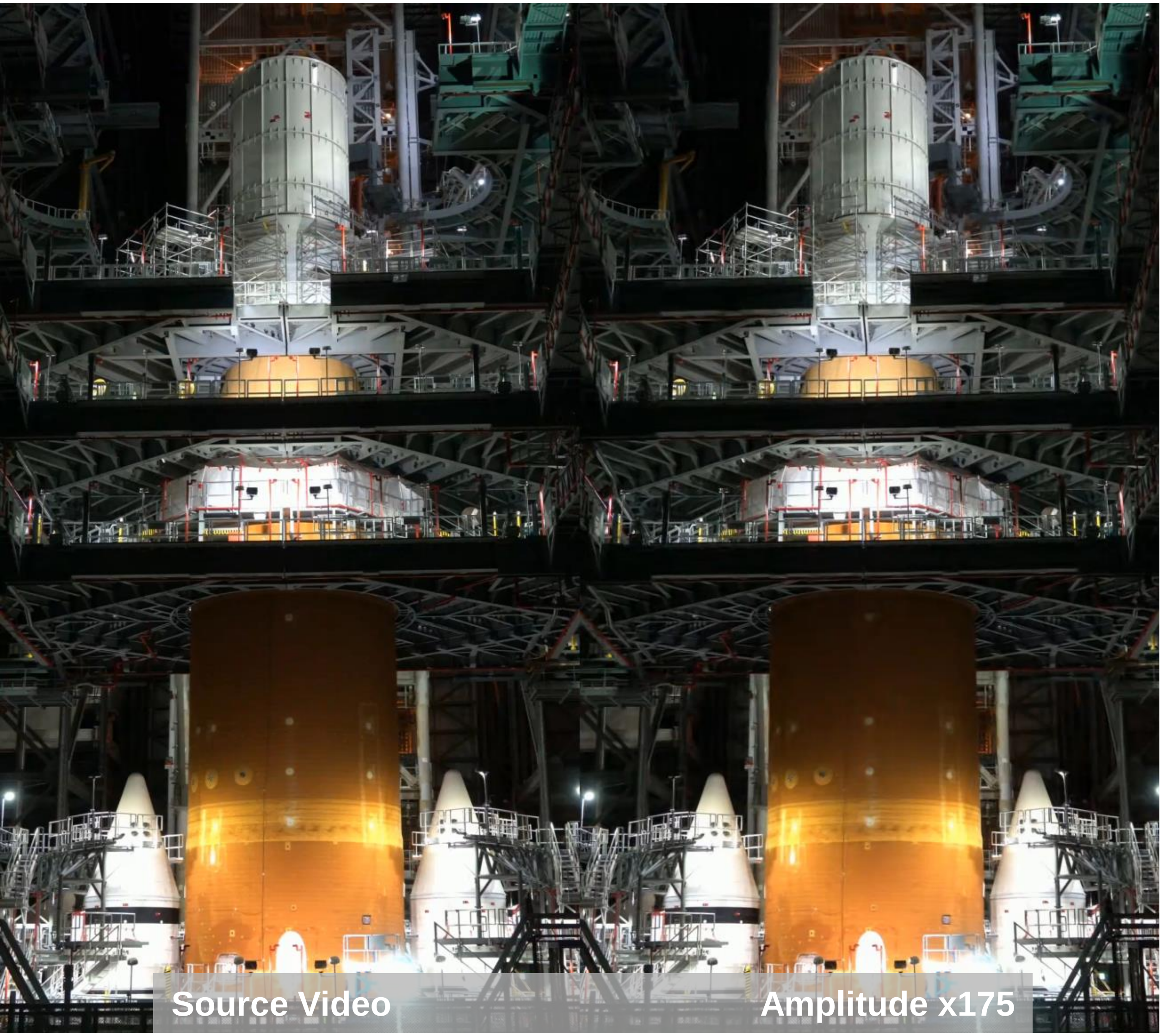


Vehicle Pitch Mode

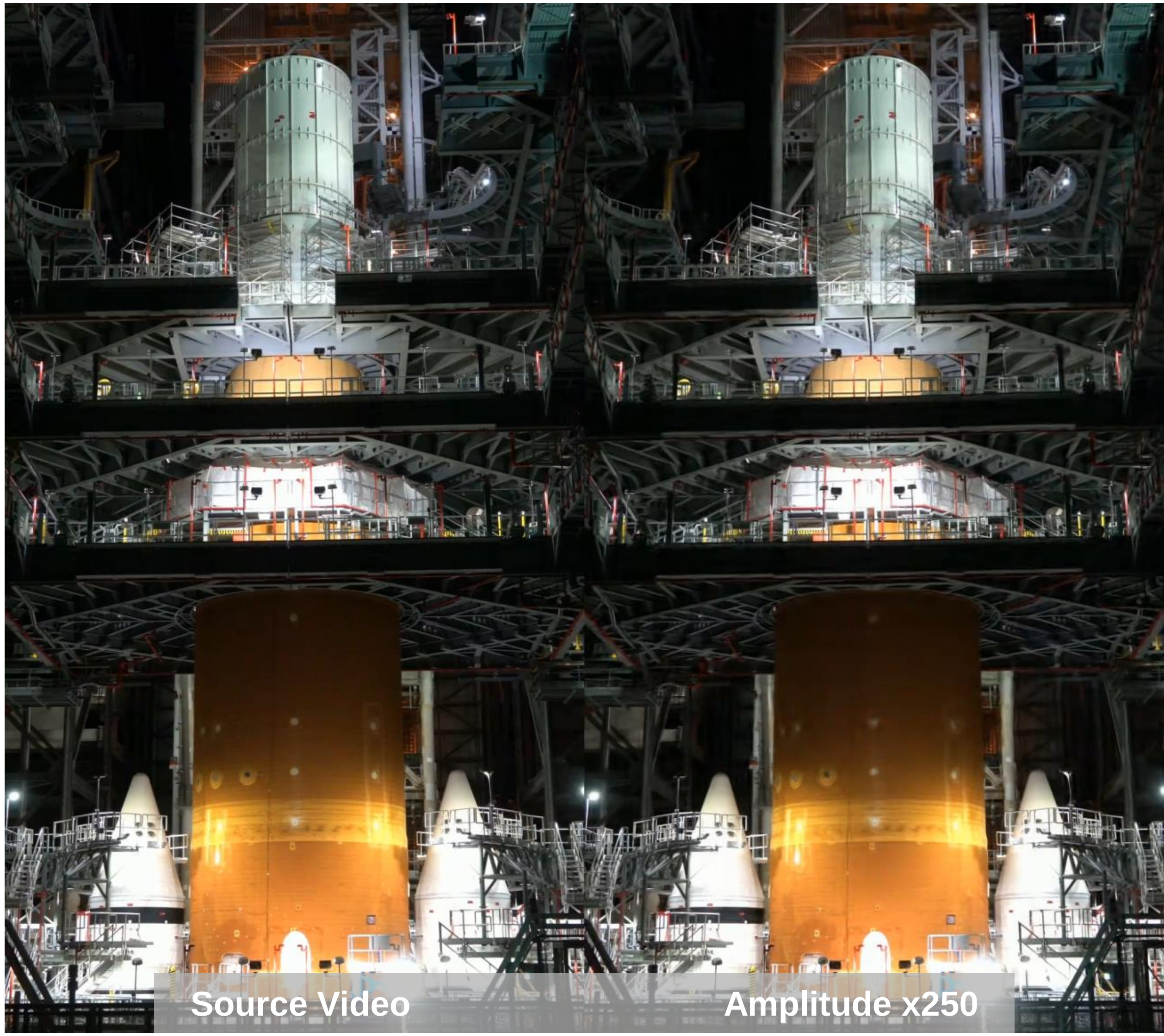


Vehicle Yaw Mode

Bending Modes – 10-Point Test



Vehicle Pitch Mode



Vehicle Yaw Mode

Aft SRB Struts: Setup and Background

Measurement location

- **A torsional mode of the vehicle was measured at a lower than expected frequency relative to the model**
- **Loads and Dynamics team came up with a hypothesis that free-play in the Aft SRB-Core joints would account for the difference**
- **The "Motion Magnification team", supporting the IMT to collect video for research purposes, was dispatched to try and collect video to see if this hypothesis could be confirmed**

View of Left SRB Connection

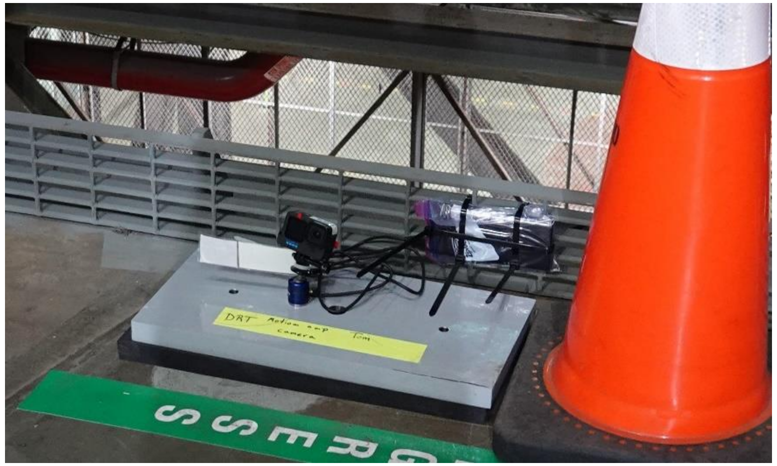
View of Right SRB Connection

SRB: Solid Rocket Booster
IMT: Integrated Modal Test

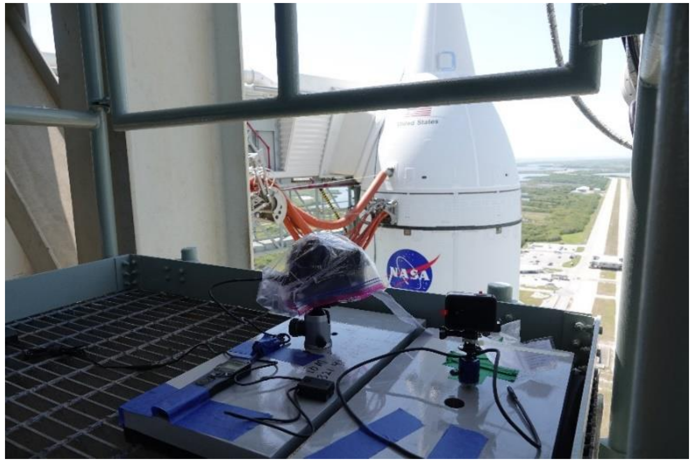
Aft SRB Struts: Motion Magnified Video

Goals of Cameras at DRRT

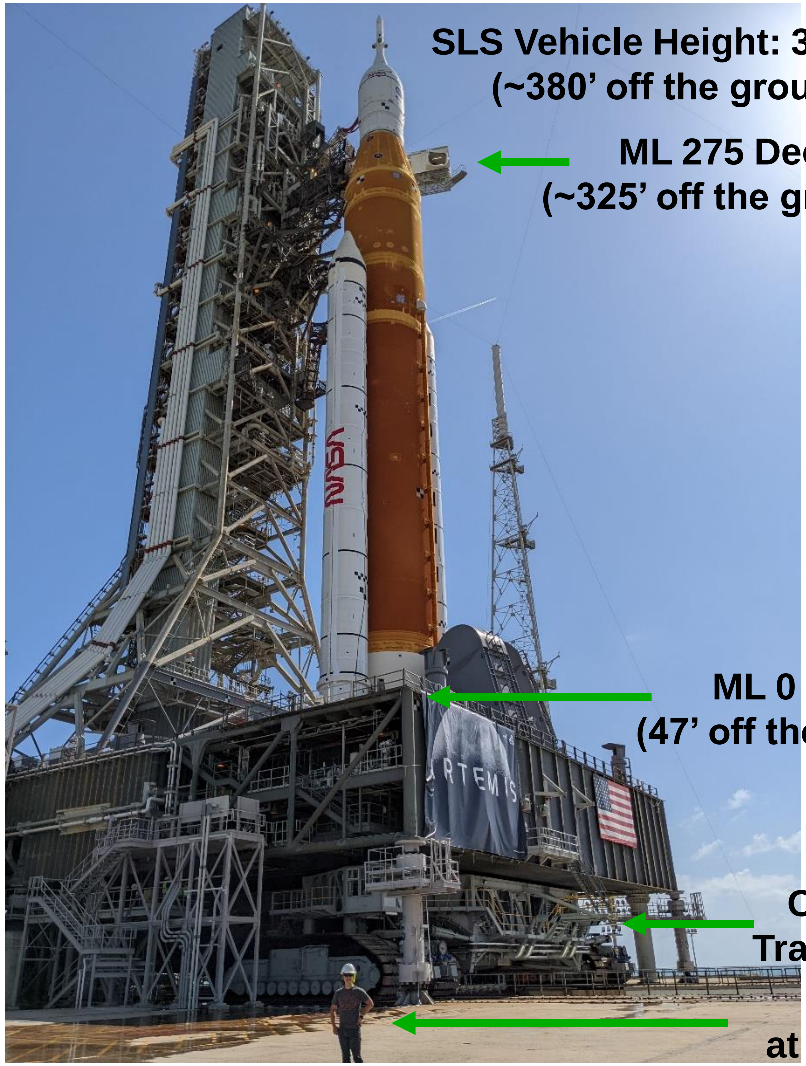
- **Goals for motion magnified camera measurements**
  - **Capture operational vibration modes**
  - **Measure motion between the vehicle and the ML tower**
  - **Look for slop in the aft SRB strut connection**
- **Instrumentation is placed in two locations**
  - **ML 0 Deck to look at the aft SRB struts and measure operational modes**
  - **ML 275 Deck to measure vehicle and tower relative motion**



Camera Placement on 0 Deck



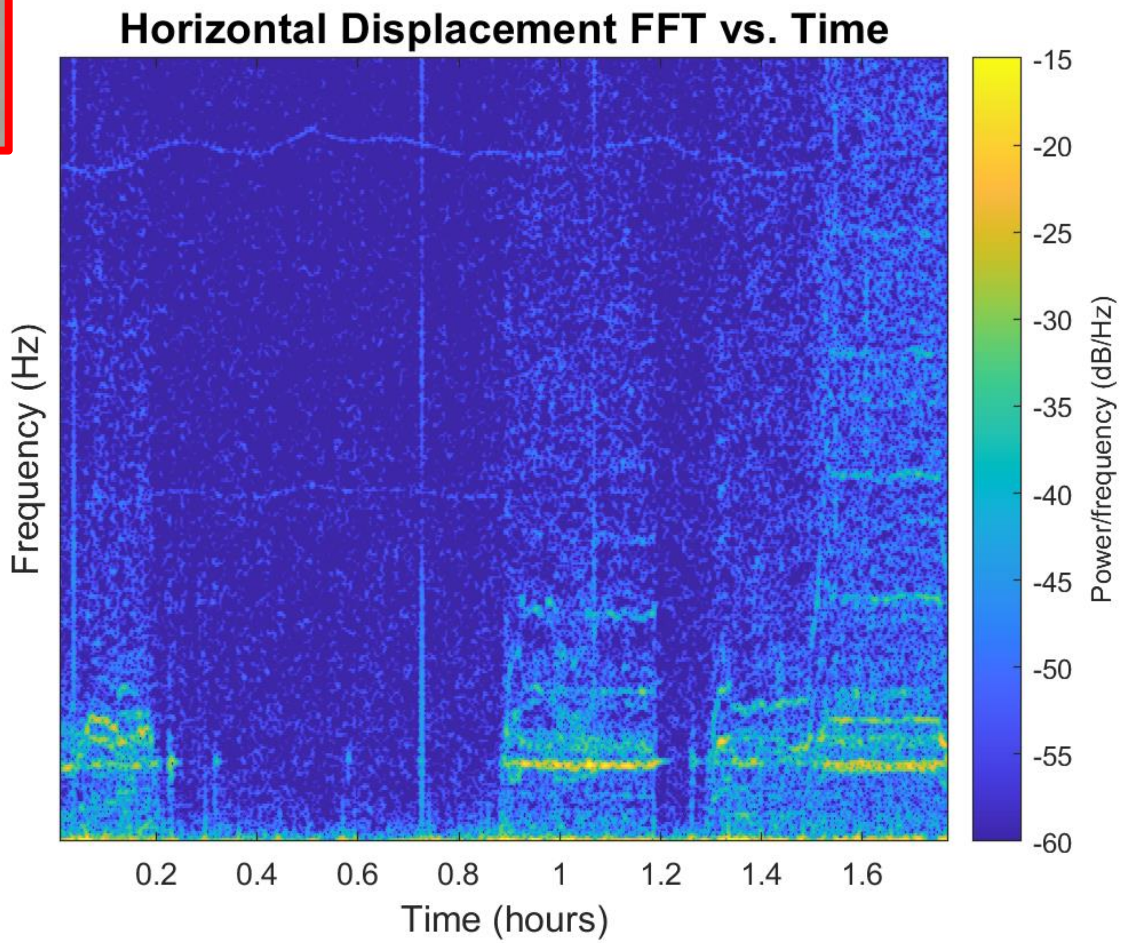
Views from 275 deck of ML Tower

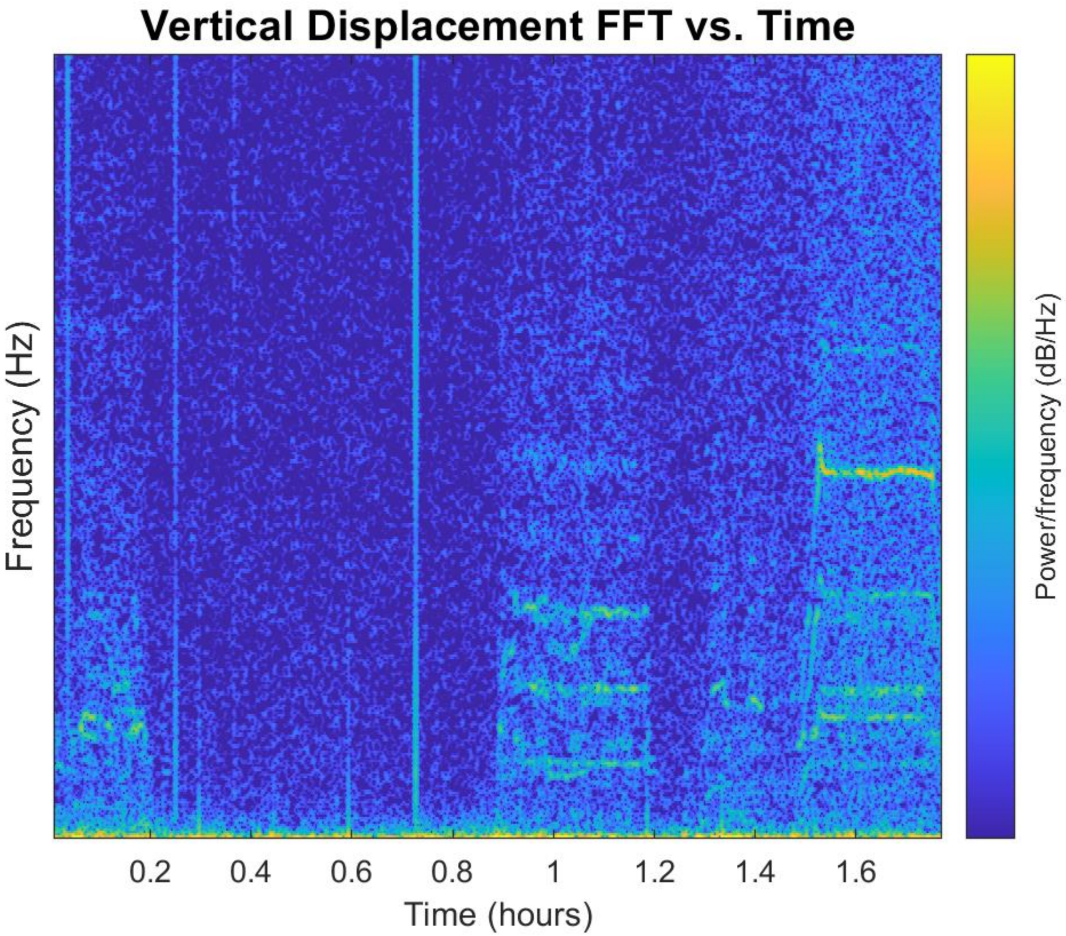


SRB: Solid Rocket Booster
ML: Mobile Launcher

DRRT: Dynamic Rollout/Rollback Test
SLS: Space Launch System

Spectrograms from ~6:05pm to 7:51pm

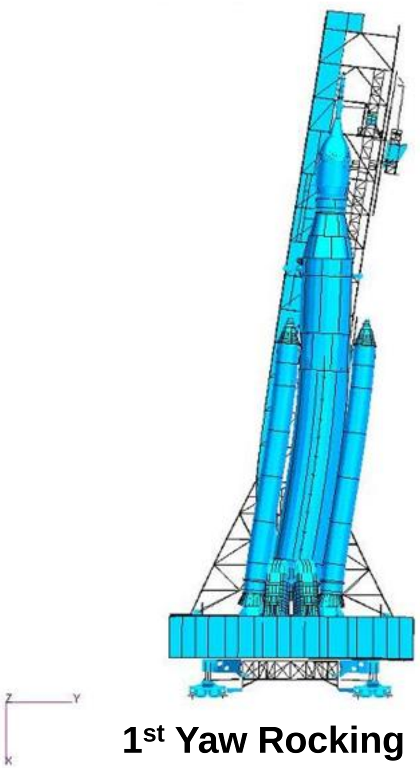




Spectrograms show the initial rollout of the VAB, stopping for the crew access arm retract, and ramping up in speed.

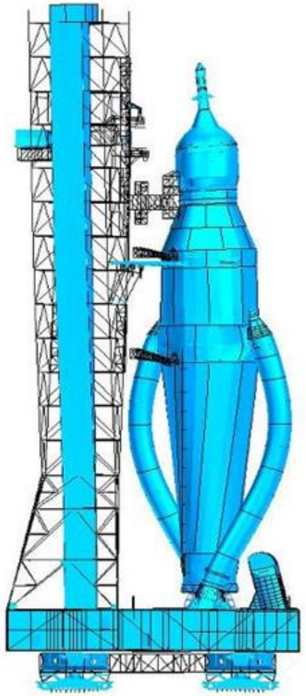
VAB: Vehicle Assembly Building

1st Yaw Rocking Amplitude x50



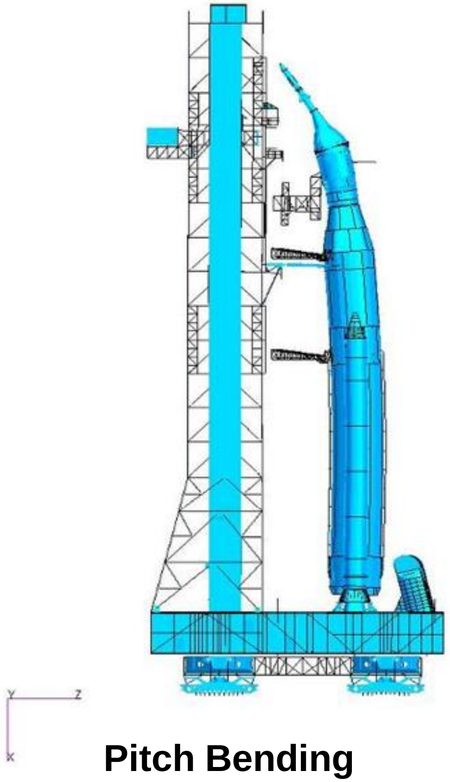
1st Yaw Rocking

Suspected Torsion Mode, Amplitude x100



Torsion

Pitch Bending, Amplitude x100



Pitch Bending

Pitch Mode Amplitude x30

Lessons Learned

- Make a checklist for what you need to do and items you need prepared
- Camera triggering can be complicated, especially if they can’t be triggered manually
- Even if everything is working perfectly in testing, have a backup if the video collection opportunity is a one shot deal
- Lighting matters. No light, no reliable video. Use a fixed/manual focus to account for autofocus in changing light conditions.
- Power – batteries or wall power, figure out your power situation where you are testing. Do a test at home to figure out endurance (both power and storage) and see if you have any overheating issues.

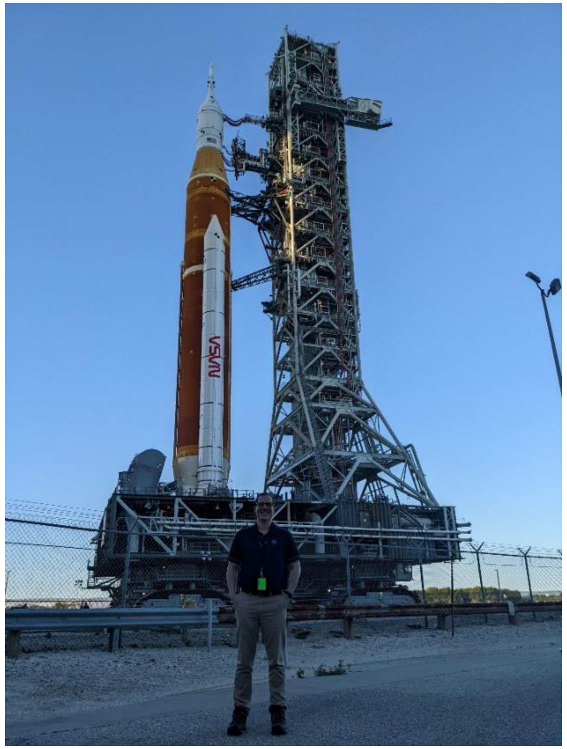
Conclusions

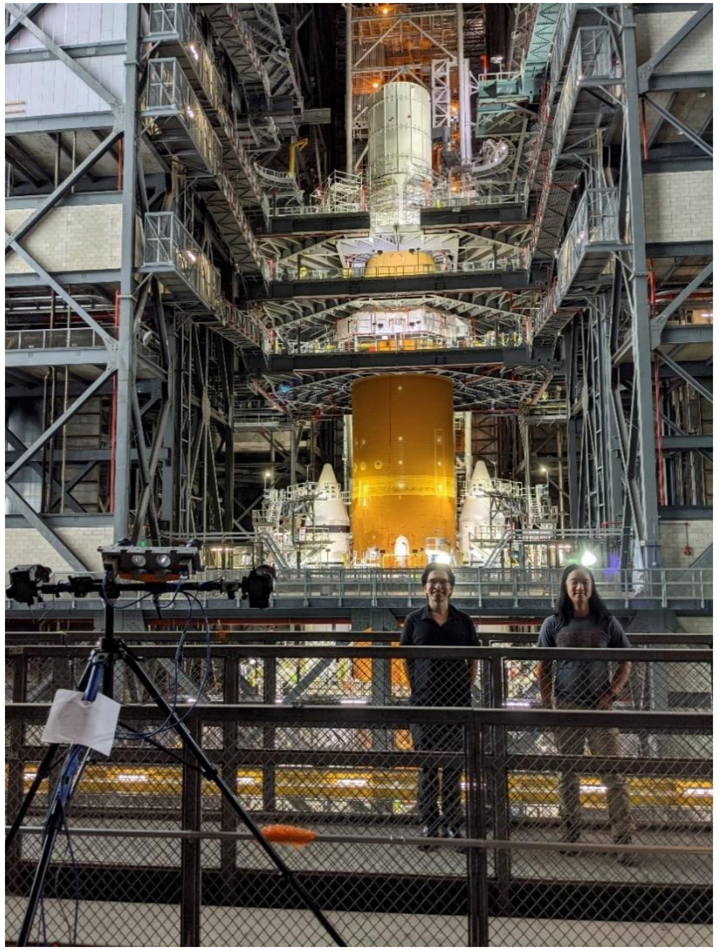
- **Consumer cameras were used during modal testing of the Space Launch System to capture operational vibration modes**
- **Testing took place during both in a controlled environment (IMT) and during a test of opportunity (DRRT)**
- **Cameras and motion magnification offer much more flexibility than traditional sensors because of the ease of repositioning and wide field of view**
- **Motion magnification can be used to identify operational vibration modes of large space structures and is an effective tool to quickly troubleshoot unexpected physics during vibration testing**

IMT: Integrated Modal Test
DRRT: Dynamic Rollout/Rollback Test

Acknowledgements

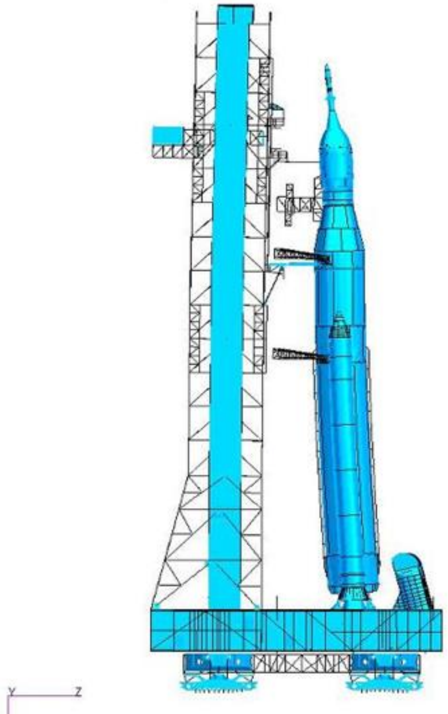
- **Tom Erdman, NASA MSFC**
- **Dan Lazor, NASA MSFC**
- **JR Booker, NASA MSFC**
- **Katrina Magno, formerly MIT LL, camera system software**





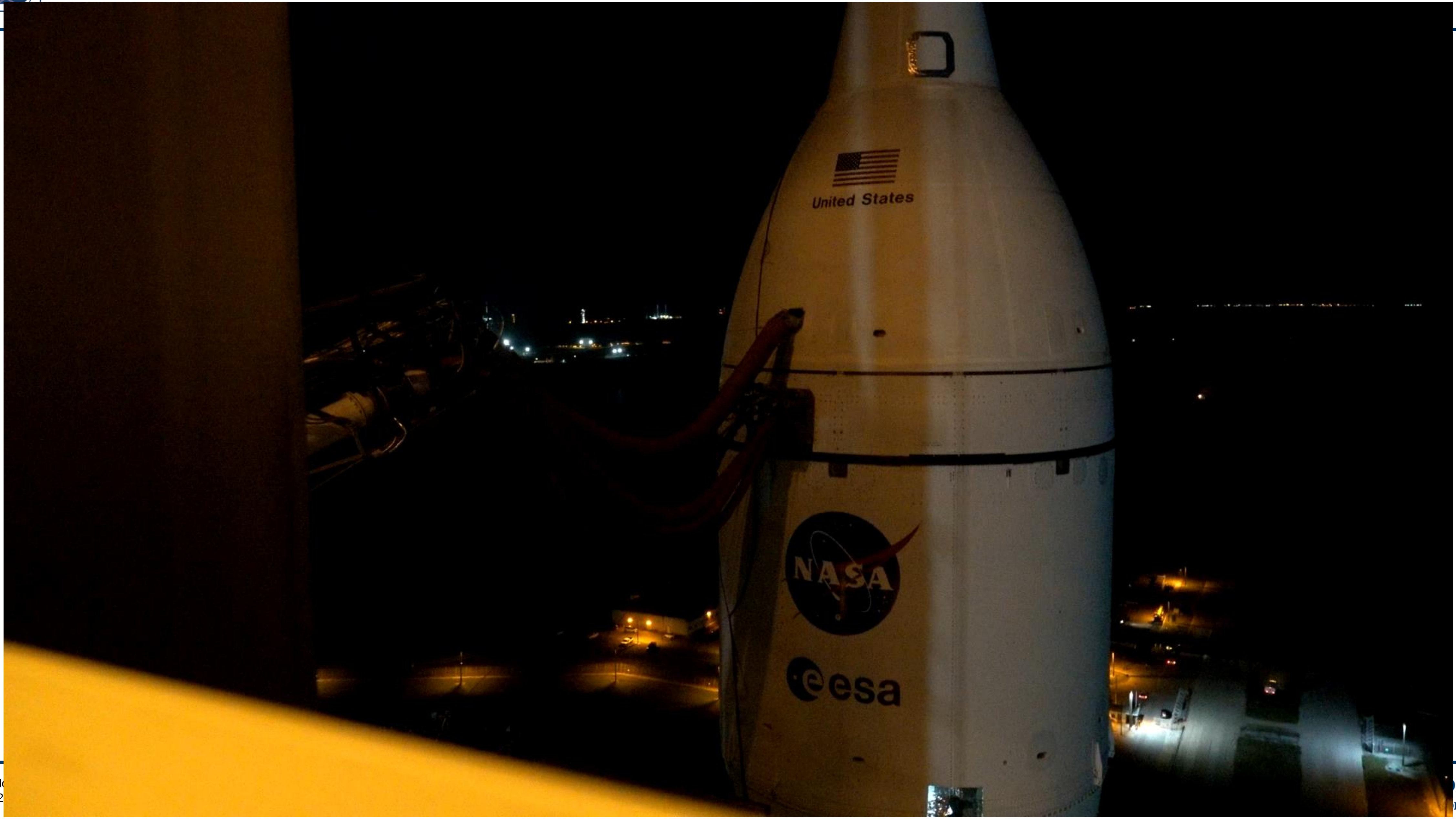
Extra

Pitch Rocking/Bending Mode, Amplitude x200



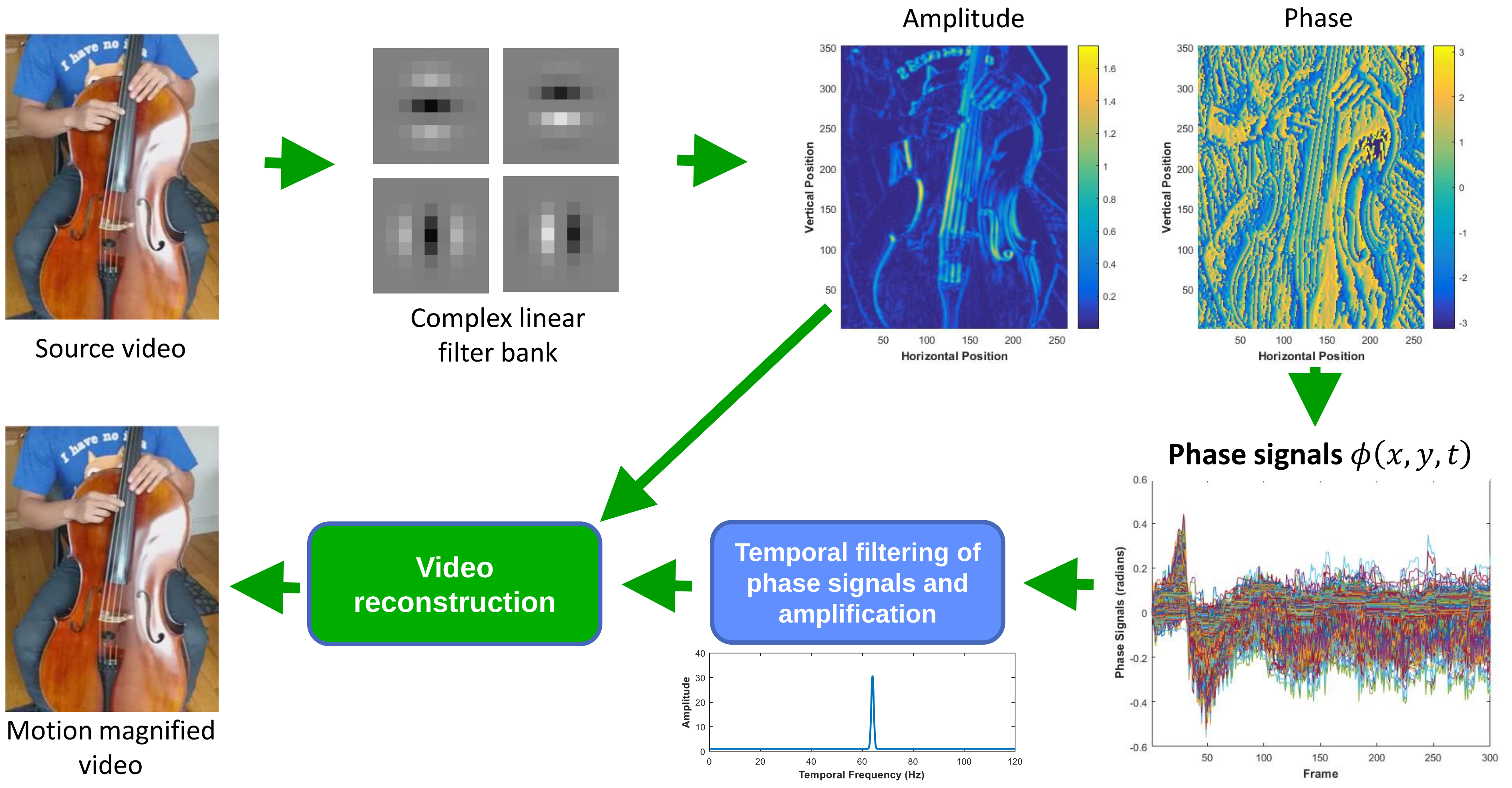
Pitch Rocking/Bending

Yaw Mode Amplitude x5



Motion Magnification: Example

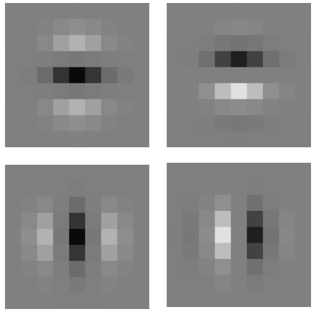
Motion Magnification Visualization Theory



Wadhwa, Rubinstein, Durand, Freeman, SIGGRAPH 2013

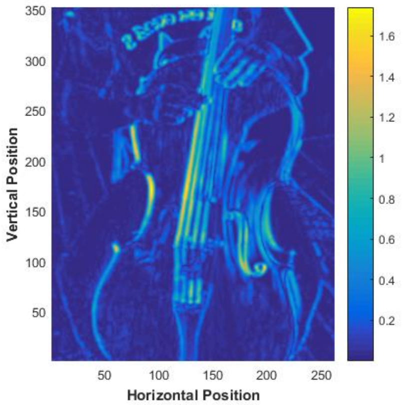
Extracting Displacements from Video

Source video

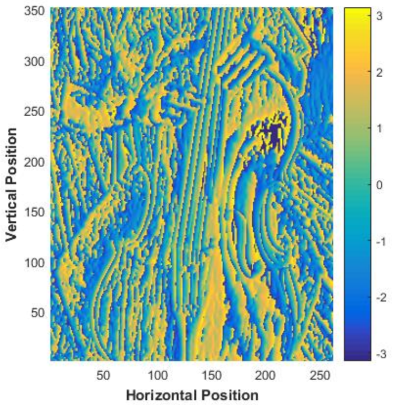


Complex linear filter bank

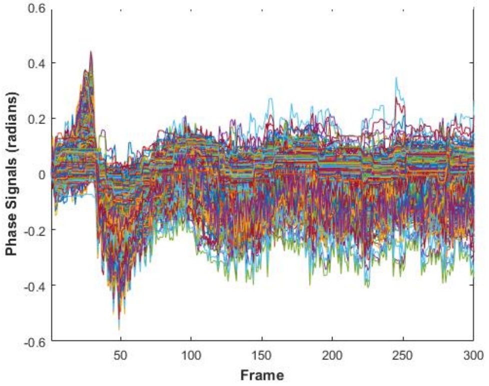
Amplitude



Phase



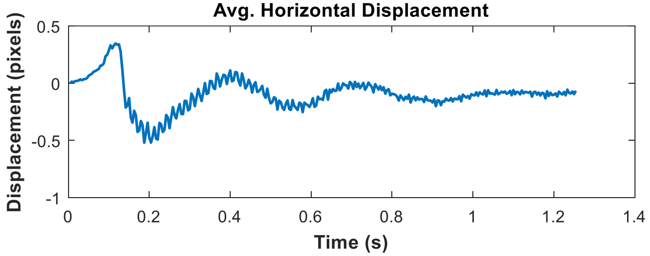
Phase signals $\phi(x, y, t)$

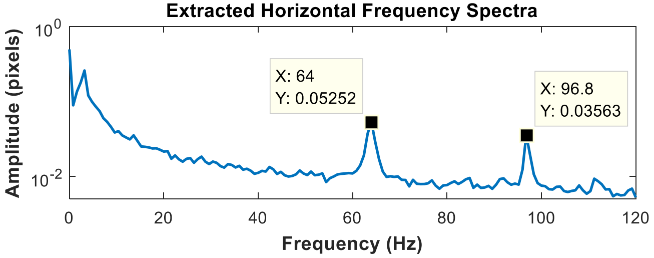


Phase-based optical flow

Assuming constant illumination,
phase contours correspond to motion signal
[Fleet and Jepson 1990]

$$displacement = \phi(x, y, t)\left(\frac{\partial \phi}{\partial x}\right)^{-1}$$

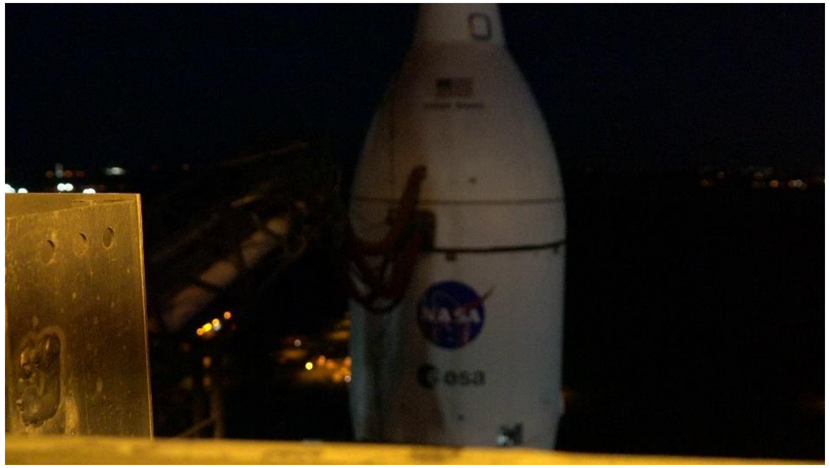




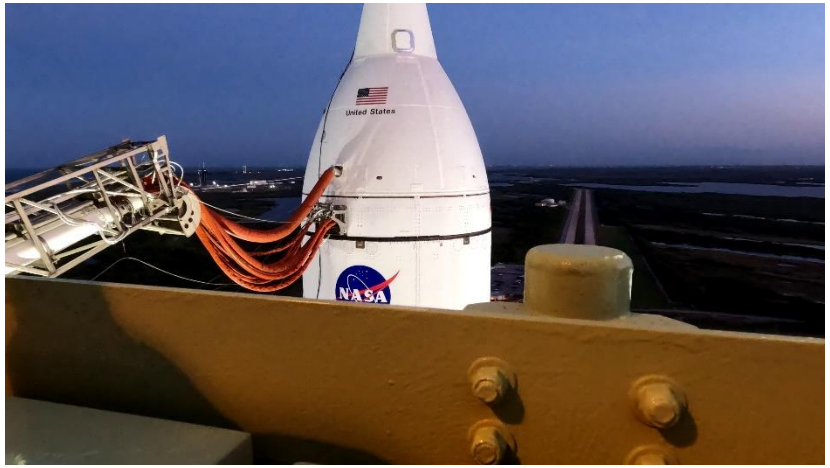
Chen, Wadhwa, Cha, Durand, Freeman, Buyukozturk, JSV 2015

Rollback Example Imagery

Left Sony Camera Field of View



Left Sony Camera Field of View



Right GoPro Camera Field of View

Left GoPro Camera Field of View

Right Sony Camera Field of View

Right Sony Camera Field of View